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Microsatellites And Improved Acquisition Of Space Systems

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Abstract. Traditional Department of Defense (DoD) practices in the acquisition of space systems have focused on advanced versions of proven technology, meaning large satellites. This paradigm contributes to dependence on a handful of satellites, program schedules measured in decades, and the expensive oversight and program management functions which must be applied to systems which, since there are so few assets, cannot countenance failures. The escape from this paradigm is offered by Microsatellites (Microsats). Microsats are not only useful technology, but technology which enables a different approach to acquisition. What the authors call the Microsat Acquisition Paradigm (MAP) is partly modeled on NASA's "Faster, Better, Cheaper" approach and takes lessons from NASA's successes and failures. Now that some space functions can be undertaken by low-cost Microsats, the advantages of mass production, reduced government oversight, and acceptance of a reasonable failure rate can be applied to space system acquisition. This paper explores the three pillars of the MAP approach: requirements, technology, and acquisition, which together support the Holy Grail of space system affordability. Understanding the military's space requirements is the first pillar of this approach. The second pillar is the ability to correlate the requirements to the current and projected state of Microsat technology and explain what space functions can be accomplished with Microsats. Finally, historical examples, as well as recent studies, demonstrate that streamlined, cost-effective acquisition is a reality for Microsats, enabling savings in time and money compared to the acquisition system used for traditional space systems.

Introduction

The U.S. government has been purchasing space systems from contractors for over four decades. In this time, the cost has only increased, the time to purchase space systems has multiplied manyfold, and the Government's satisfaction with its purchases has, if anything, declined. Current acquisition reform efforts, while welcome, have not solved this problem.

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It is vital, in this era of expanding needs and contracting budgets, to examine how we purchase space systems and how a new model of space system acquisition can reduce costs and timelines while increasing satisfaction. This paper makes the case for the Microsat Acquisition Paradigm (MAP). Through analysis of requirements, technology, and acquisition, the MAP leads to a proper examination of Microsats as solutions and to applying lessons from Microsat programs to space systems in general. (Figure 1)

For purposes of this paper, a Microsat is a single-purpose satellite, normally but not exclusively under 100 kilograms (kg) in total mass.

The MAP rests on three pillars: Requirements, Technology, and Acquisition. To understand all these, we must first take a quick look at the historical record for military Microsats and the reasons why lessons drawn from Microsat programs are relevant and important.



Figure 1. Microsat Acquisition Paradigm

Historical Background

Every era since the Space Age began in 1957 has produced fluctuations in the preferred method of developing and acquiring space systems. As the military uses of space have expanded, DoD has sought to develop ever-increasing space capabilities. Most often, these come in the form of enlarging and adding capability to past satellite designs and/or technology.

The idea of using Microsats for military missions is not new. Many of the first U.S. military satellites were Microsats. In the early 1960s, Microsats provided the first military communications systems, the first missile warning system, and performed a host of other military functions, some of them still classified.

As boosters became more powerful from the late 1960s on, the U.S. military chose to orbit increasingly larger and more capable payloads. In the decade from 1978 to 1987, for example, only six military Microsats were launched. Beginning in 1987, the Defense Advanced Projects Research Agency (DARPA) led a resurgence of interest which resulted in such satellites as GLOMR, MACSAT, DARPASAT, LOSAT-X, and the MicroSat constellation. (Table 1)

When the Persian Gulf crisis began in the summer of 1990, DARPA's 68-kg Multiple Access Communication Satellite (MACSAT) was being tested in orbit. The MACSAT was pressed into operational service and assigned to the exclusive use of a squadron of the 2nd Marine Air Wing. Throughout Desert Shield and Desert Storm, the squadron used the MACSAT to exchange logistics information, such as supply orders, with its U.S. headquarters.

Despite the success of the MACSAT and other Microsats, however, the military did not rush to put more Microsats into service. In 1992, Congress deleted funds for a Navy program to orbit six MACSAT-based Arcticsat UHF relay Microsats.¹

While military Microsats performing operational missions are still rare, R&D use has continued, and several innovative missions are pending. Notable among these are two projects backed by the Air Force Research Laboratory (AFRL): the XSS-10 space inspection Microsat and the pathfinder mission for the TechSat-21 radar sensing constellation.

Why Consider Microsats?

Microsats offer a wide range of capabilities. It must be admitted up front that Microsats also have certain limitations. In communications, for example, Microsats have limited data transmission capabilities compared to largesats. To make them equivalent, one would have to downsize a largesat's entire communications payload (at high R&D cost) or keep the Microsats simpler and make more use of ground processing or existing communications relay pipes like the NASA Tracking and Data Relay Satellites. The increased use of ground-based support systems is the approach taken by most Microsat programs.

In Microsats' favor, they offer lower total mission costs than largesats and can be built and launched more quickly. In some mission scenarios, especially those where on-orbit capacity must be added or replaced rapidly, these characteristics make Microsats well worth considering as part of the military space fleet.

TABLE 1. Selected Military Microsatellites

Selected Military-Related Smallsats and Microsats			
NAME	YEAR	MASS (kg)	PRIMARY PAYLOAD
U.S.			
GLOMR	1985	52	Comm
MACSAT*	1990	68	Comm
REX	1990	50	Comm
SECS	1990	25	Comm
MicroSats (7 satellites)	1990	23 (each)	Comm
LOSAT-X	1991	75	Sensing
MSTI-1	1992	150	IR Sensing
RADCAL	1993	90	Radar Calibration
MSTI-2	1994	169	IR Sensing
REX-II	1996	110	Radiation Sensing
FORTE	1997	215	RF Sensing
MightySat I	1998	68	Technology Testing
TSX-5	2000	115	Technology Testing
MightySat II.1	2000	140	Imagery
XSS-10	2001	25	Satellite Inspection
FOREIGN			
CERISE (France)	1995	50	ELINT
OFEQ-3 (Israel)	1995	189	Imagery
Clementine* (France)	1999	50	ELINT
* NOTES: - 2 MACSATs were launched: one failed due to operator error. - France's Clementine satellite has no relationship to the U.S. Clementine program.			

To provide a comparison in one mission area – communications satellites – it would cost approximately \$38 million (M) to buy eight commercial off-the-shelf (COTS) Orbcomm UHF/VHF comsats and launch them using a Pegasus

launch vehicle. Eight Orbcomms would provide continuous or near-continuous coverage of a theater of operations.² (NOTE: All costs in this paper, unless otherwise identified, are in Base Year 2000 (BY00) dollars.) In contrast, the average unit cost of a single UFO satellite, designed to handle UHF communications from geosynchronous orbit, is \$212M.³

A UFO has much greater capacity than an eight-Orbcomm constellation and carries voice traffic, which the Orbcomms do not. If the UFO fails, however, its entire capacity is lost and will take months or years to replace, at a cost similar to the original. In a war, that kind of time may not be available. The ability to quickly and affordably replace even a fraction of lost capacity could be crucial. The satellite assembly line at Orbital Sciences Corporation (OSC) turns out a batch of eight Orbcomms every three months, and the same company's Pegasus assembly line averages one launch vehicle produced every one and a half months. Both Orbcomm and Pegasus are designed for storability and rapid checkout and launch. By comparison, a UFO takes 12-18 months for satellite construction alone.⁴

In addition to the shorter manufacturing timeline, the relative simplicity of Microsats enables them to be stored ready for launch much more cheaply and easily than largesats. This capability for responsiveness is not only an advantage compared to largesats, but offsets the potential vulnerability created by the fact that Microsats most often operate at LEO altitudes which could be more susceptible to antisatellite (ASAT) systems.

Wertz and Larsen's book *Reducing Space Mission Cost* offers an instructive comparison between the costs of four missions estimated using standard spacecraft development approaches and parametric costs vs. what actually happened when the missions were done using the smallest possible spacecraft and a MAP-like approach. (Note that most of the spacecraft shown in Table 2 are larger than the 100-kg guideline mentioned early in this paper, making the point that a Microsat is more a matter of design philosophy than of an arbitrary size limit.) Clementine in particular was a fairly complex spacecraft, but cost two-thirds less than a comparable largesat and took only 22 months to build and launch using a streamlined acquisition and development approach.

From an acquisition standpoint, the more complex system (a largesat) needs a much larger effort by the Government in supervision, management, and paperwork. One military space official explained,

"Big satellites carry multiple payloads. The mass of the interface control documents exceeds that of the spacecraft and approaches the weight of the launch vehicle."⁵

Table 2. Spacecraft cost comparisons
(All figures FY95\$M)⁶

Spacecraft	Expected Cost	Actual Cost
Orbcomm (2 prototypes, each 33 kg)	375.8	15.7
RADCAL (radar testing, 92 kg)	112.7	16.6
AMSAT OSCAR-13 (communications, 140 kg)	127.4	1.24
Freja (magnetospheric research, 256 kg)	271.2	24.5
Clementine (BMDO test and lunar science, 232 kg (dry))	233.9	85

NOTE: All missions include launch costs. All except RADCAL include first-year operations costs.

It is a fact that large spacecraft require large, expensive launch vehicles. This leads to a natural desire to make full use of every kilogram of payload capability. Spacecraft designers, squeezed between the need to minimize weight and the requirements for redundancy, space-qualified parts, and other standard rules, make it work by designing unique structures, one-of-a-kind components, and very little design margin.⁷ The result is incredibly expensive spacecraft. Microsat designers, paradoxically, focus less on squeezing the most out of the available payload capacity and more on hefty design margins, overbuilt structures, and proven (though rarely space-qualified) components. All these are made possible by the focus on using the simplest possible spacecraft for the job and relying on functional or system-level redundancy. (Functional redundancy is the capability of one part to do the job of another, such as using a horizon sensor to adequately, if not perfectly, replace a damaged star tracker.) The need for expensive launchers for large satellites also means there are very few launches, leading to even more costs as designers try to cram more functions onto the handful of spacecraft that will actually get launched.

The 1994 Air University study *Spacecast 2020*, in a section titled "Rapid Space Force Reconstitution," made another point. If a large satellite has a nominal 10-year life and a Microsat two years, the Microsats are able to go through five generations of technology improvement for every one generation of the largesat.⁸ It should be noted that Microsats do not *have* to have short life spans: the design life of an Orbcomm is eight years.⁹ There are tradeoffs between updating technology and the added costs of launching waves of shorter-lived satellites, but a Microsat approach at least provides the flexibility to examine that tradespace. Large satellites do not.

It is highly significant that all three of the major space-related forecasts accomplished in recent years by the Air Force - *New World Vistas*, *Spacecast 2020*, and *Air Force 2025* - endorsed development and use of Microsats for some military missions.¹⁰

In *New World Vistas*, the Air Force's Scientific Advisory Board made the following points about the Air Force's future space systems:

- To hold down costs, single- or dual-purpose satellites should be the rule.
- Time from design start to launch should be held to two years to reduce cost creep and allow for maximum practical infusion of new technology.
- Advances in computers, sensors, and materials will enable large constellations of small satellites to be integrated for global, real-time sensor and communications coverage.
- Future spacecraft should be inexpensive, mass-produced, networked with other space assets, and highly autonomous.¹¹

Spacecast 2020, mentioned earlier, recommended the use of small satellites combined with rapid-response launch vehicles to provide a timely reconstitution capability.

The *Spacenet* section of *Air Force 2025*, which describes the future on-orbit C3 system, states, "Design goals in 2025 may move toward distributed small Microsatellite systems, reusable Microsat systems, or disposable Microsat systems, as well as retaining some large, maximum-longevity space systems."¹² The report noted that Microsat technology in 1996 was immature, but suggested that the cost of future Microsats could be measured in thousands of dollars. "Throwaway" Microsats could be launched on need and discarded after a crisis.

The magnitude of the cost and size increases in military satellites is most evident in the military satellite communications (MILSATCOM) field. The Initial Defense Satellite Communications Program, first launched in 1966, used low Earth orbit (LEO) satellites with limited capabilities. As an Aerospace Corporation reference explains it,

"The basic design principle for IDSCP was simplicity. By using spin-stabilized satellites in subsynchronous orbits, neither stationkeeping nor active attitude control was required. The random nature of the individual satellite orbits provided automatic replacement of failed satellites with acceptable outages. No command system was used because of previous experiences (with failures). Each satellite had two TWTs (traveling wave tube amplifiers), and an onboard sensor switched from one to the other upon detecting a failure. The two TWTs were of different designs to reduce the chance of a common failure mode."¹³

The 45-kg IDSCP satellites had a threshold life of one and a half years, and had a built-in device to turn them off after six years. Several satellites operated far beyond these lifetimes, and satellites launched in 1968 remained in service in 1976. (It should be noted that one criticism of this system was the low production and relative unreliability of the power systems then available which could fit on such a small satellite. However, battery and solar-cell technology has improved immensely since 1966. The improving state of technology is important to keep in mind whenever historical examples of Microsats are considered.)

The IDSCP system was later renamed Defense Satellite Communications System (DSCS) I. DSCS II and III steadily increased the size, capability, and cost of the MILSATCOM platforms. Today's UHF Follow-On (UFO) satellites weigh 3015 kg and cost \$212M each, while the MILSTAR satellites weigh 4500 kg and has a unit cost of \$808M. (The MILSTAR figure is the cost *after* the program managers claim to have saved a total of \$606M through performance trades and improved acquisition procedures.)¹⁴ In essence, complexity costs!

We have purchased greatly increased capability for this added size and cost. However, it is appropriate to examine the total price paid for this complexity, and how this is intertwined with the approach taken to spacecraft acquisition.

Current Acquisition Approach

In the last few years, it became apparent that efforts to root out fraud and waste in contracts cost, in some cases, more than they were worth, thanks to the layers of bureaucracy these efforts added. Recent acquisition reform efforts have emphasized reduced oversight, Government-contractor teaming, and increased contractor responsibility. These efforts have improved the acquisition process for space systems, but have not created the kind of fundamental paradigm shift sought in the MAP. Acquisition practices still add considerable cost to military space systems.

Many examples of current acquisition practices are combined in the templates built into one of DoD's standard cost estimating systems, Automated Cost Estimating Integrated Tools (ACEIT). ACEIT can take the estimated hardware cost of a system, plus the anticipated development and acquisition schedule, and use recent experiences to extrapolate the Life Cycle Cost (LCC) of a system. By using ACEIT as an example, we can examine these costs for a new system by averaging the actual experience involved in buying many existing systems.

Costs and Examples

The results of one study employing the ACEIT tool demonstrate both the potentially low cost of military Microsat systems and how far space system acquisition has to go in reducing non-hardware costs.

The Air Force Research Lab (AFRL) awarded a contract to the Universities Space Research Association (USRA), which in turn contracted with Space Dynamics Lab (SDL) of Utah State University, to support the "Innovative Design, Low Cost Nanosatellites" task. The objective of the program, called Advanced Space Technologies and Emerging Concepts (ASTEC), was to determine the feasibility and costs associated with the development and manufacture of 100 Microsats to perform a reference mission specified by AFRL with a cost goal of \$1 million per satellite. SDL aggressively pursued the design using an innovative leading-edge Satellite Development Approach (SDA). The overall goal was to develop new manufacturing and integrated life-cycle development methodologies as well as incorporate proven strategies into their SDA.

The ASTEC study, based on mass production of technologically advanced 40-kg Microsats with rendezvous, inspection, and docking capabilities, produced these results:

Hardware RDT&E cost: \$43M
Total RDT&E: \$75M
Hardware Production: \$26M
Total Production: \$50M

These results are extremely impressive for a highly capable system of 100 Microsats. They show what applying volume production and the latest Microsat technology can do for spacecraft costs and capabilities.

Buying the Government Way

While the above figures show how economical Microsats can be, they address only one component of a satellite system - the hardware. When the government buys a space system, it adds numerous costs for oversight, evaluation, etc.

In the RDT&E and Production phases, costs to the Government other than the satellites consist of Launch; Ground Command, Control, Communications & Mission Equipment; Flight Support Operations & Services; Storage; Systems Engineering/Program Management; System Test & Evaluation; Training; Data; Peculiar Support Equipment; Common Support Equipment; Operational/Site Activation; Industrial Facilities; Initial Spares and Repairs; Engineering Change Orders/Engineering Change Proposals; and Government Program Office. System Engineering/Program Management (SEPM) includes systems engineering and technical control as well as business management of particular systems and programs. The cost labeled Government Program Office includes the expense of the Government System Program Office (SPO). A SPO is the office of the Program Manager, and the single point of contact with industry, Government agencies, and others in the System Acquisition Process.

In the example just discussed, the total acquisition costs were forecast at \$125M. This is a premium of \$75M over the initial costs of the hardware, arrived at by using current DoD acquisition procedures as costed by ACEIT based on historical examples and Cost Estimating Relationships (CERs). The magnitude of the difference between hardware costs and total costs demonstrates how important the Acquisition pillar of the MAP is in reducing costs.

Another ANSER study, completed in 1997, examined a complete force of Microsats and rapid-response

small launchers based on retired missile stages. The purchase included eight complete constellations (each with seven UHF communications Microsats for continuous connectivity), nine larger store-and-forward communications Microsats, and 37 launch vehicles (the extra vehicles were to allow for a future generation of satellites in addition to those initially purchased.) All the satellites used were available off-the-shelf from commercial vendors. Cost analysis yielded the following results:

Hardware RDT&E cost: \$21M
Total RDT&E: \$45M
Hardware Production: \$323M
Total Production: \$450M

Other Factors

In addition, recent space system acquisition has rarely gone as planned, so the actual costs are higher than the projected ones. In part, this is due to the increased complexity of the desired systems, and in part to the cumbersome system by which we purchase them.

Another problem is the number of competitors involved in purchasing space systems. In 1997, for the follow-on to MILSTAR, the Advanced Extremely High Frequency (AEHF) program, the Government received only two proposals. Today, if the DoD wants a large, complex satellite, only Boeing/Hughes, Lockheed-Martin, Space Systems Loral, and TRW (among American companies) have the capability to develop it. Any concept involving Microsatellites adds several other possible manufacturers, increasing the prospects for competition and bring into the mix organizations with a reputation for innovative low-cost solutions.

As noted earlier, the increasing weight and complexity of space systems has continuously driven up the cost of acquiring them. Some increase in acquisition cost and schedule is expected any time a more complex system is purchased, so we must look for the solution in two areas: buying the least complex technology to do the mission, and purchasing it in the simplest, most affordable manner.

Example: An Early Military Microsat Program

At this point, we need to return once more to the lessons of history. We are *not* arguing that there were "good old days" in which all space acquisition worked smoothly. The Air Force's MIDAS satellite, designed in a program which began in 1958 to detect missile launches, was an example of a program subjected to

subject to repeated cost and schedule increases. The 1840-kg MIDAS, however, was a very large, complex spacecraft for its time, one that pushed the state of the art.

Contrast that experience to a system which, while admittedly facing much lower technical hurdles, also broke new ground for military space systems. This was the first signals intelligence satellite program, publicly announced as a solar radiation satellite program called SolRad. In fact, these satellites were also designed to intercept Soviet radar signals and transmit them to ground stations for analysis. Accordingly, the project had the classified name Galactic Radiation and Background (GRAB).

The SolRad/GRAB satellites (Figure 2) were proposed in 1958. They weighed 18 kg, required little new technology, and were built mainly in-house by the Naval Research Laboratory (NRL) using the spherical "bus" from the NRL's Vanguard program. Full development began in August 1959. Launch was approved on 5 May 1960, and took place on 22 June.¹⁵

A timeline like this - nine months to build the spacecraft and six weeks to integrate and launch the payload - is unheard of in modern space systems. America's first satellite, Explorer 1, with a science payload simpler than the GRAB payloads, went from approval to orbit in 84 days (most of the spacecraft design work had been done ahead of the official start date, but fabrication had not begun.).

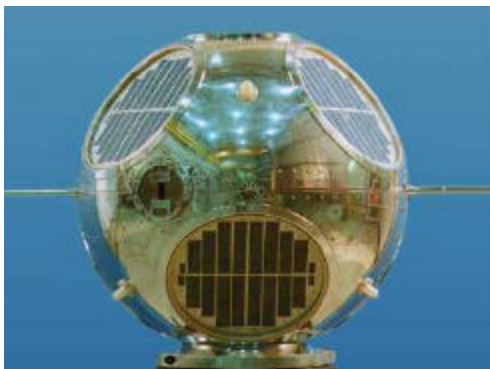


Figure 2. The SolRad/GRAB satellite. (NRL)

The SolRad/GRAB experience is an early example of what we are calling the MAP. The above-mentioned IDSCP is another example. Microsats are not the only military space systems ever delivered on time and on budget, but they have a much better record than larger space systems. Accordingly, there are lessons to be learned in both the technology and acquisition sides.

Recently, NASA attempted something similar to the MAP with its Faster, Better Cheaper (FBC) approach. FBC's record has been good with Earth orbiting science craft, less so with planetary probes. A 1999 Aerospace Corporation analysis showed that, while FBC missions had a higher failure rate than traditional large spacecraft, the magnitude of the large-program failures was so much greater that the FBC approach worked out to be 57 percent more cost-efficient, at least for NASA science missions.¹⁶ After the failure of two Mars missions, NASA appointed the Young Commission to examine the FBC approach. The Commission found the approach sound but said schedules and budgets had been pushed too hard, resulting in the skipping of tests and other unwise shortcuts.¹⁷ The Commission's recommendations stressed the importance of single-interface management structures and thorough testing programs - both, it should be noted, far easier to achieve with small spacecraft than with very complex ones.

The Microsat Acquisition Paradigm

Distilling the lessons of FBC's successes and failures, plus the records of military space programs large and small, we have developed the MAP. We will now look in depth at each of the MAP's three pillars: Requirements, Technology, and Acquisition.

Requirements

Understanding the military's space requirements is the foundation of this approach. In the past, proponents of Microsats have sometimes approached DoD with an argument like, "Look how much better this technology is." Whether they were correct or not is immaterial. DoD starts with an extensive requirements generation and validation process, and any effort to interest DoD in new technology must proceed from an analysis of those requirements.

Such an analysis was funded by Air Force Space Command (AFSPC) and performed by ANSER in 1999. The findings were that Microsats appeared to be a cost-effective solution - in some cases the preferred solution - to requirements in:

- Space control (detecting, inspecting, and, if necessary, countering spacecraft on orbit). Microsats were the preferred low-cost solution for close inspection and related missions.
- Space force enhancement (providing weather, communications, and other services to terrestrial forces). Microsats showed promise as part of the space force mix in all areas except high-resolution imagery.

- Space support (launch, on-orbit serving, and orbit transfer). Microsats could provide a near-term servicing capability and would greatly aid the launch and transfer capabilities by keeping down the size of the spacecraft being launched or relocated.¹⁸

Technology

The second pillar is the ability to correlate the requirements to the current and projected state of Microsat technology and explain what space functions can be accomplished with Microsats. Microsats also enable the use of smaller, cheaper, more responsive launch vehicles, and there are breakthrough developments possible in this field as well.

The above-mentioned Microsat study done for AFSPC in 1999 confirmed that, given the improvements in microelectronics and other technologies, there was no mission except high-resolution Earth imaging which could NOT be performed with Microsats.¹⁹ This is not to say that all missions *should* be turned over to Microsats. High-volume communications, for instance, would require so many Microsats that the savings over MILSTAR achieved by using cheaper spacecraft would be wiped out by the launch requirements. (The tradeoffs involved may still be worthy of proper examination, since the Microsats offer survivability, upgradeability, and other advantages.)

Redundancy is a concern often voiced about using Microsatellites. Microsats are often single-string designs with minimal redundant components. The point made by Microsat proponents is that Microsats rely mainly on a spacecraft-level redundancy as opposed to component-level redundancy. While many of today's Air Force weapon systems, such as cruise missiles and smart bombs, have as much redundancy as possible given their size and weight limits, the key characteristic of such devices is that they are simple enough and affordable enough to manufacture in quantity. If a weapon like these fails, another one is launched at the same target.²⁰ There is no reason the same logic should not apply to satellites. (It is relevant to note that these types of expendable, mass-produced weapons are often heavier and more complex than Microsats.)

Professor Wiley Larson, in the book *Reducing Space Mission Costs*, states the logic of simplicity this way:

"Basically, there is less that can go wrong on a small spacecraft. When we add physical redundancy...we also add the interconnects and the logic for selecting the components to be

used. All of this increases the complexity and, therefore, reduces somewhat the reliability enhancement that was intended."²¹

Larson's point about the advantage of using the simplest possible design is not a new concept. When asked by a Congressional panel in 1962 how to improve reliability and lower costs of spacecraft, George Trimble, then vice president of the Martin Company (now part of Lockheed-Martin), put it this way:

"Complexity inherently lowers system reliability simply because there are more things that can go wrong. The probability of failure increases almost directly with the number of components. The contractor, therefore, must design reliability into his product beginning at the conceptual stage by using his engineering ingenuity and resourcefulness to achieve the highest degree of simplification possible. In addition to increasingly reliability and thereby reducing costs, simplification results in substantial corollary savings in such areas as training, maintenance, and basing. It is our feeling, therefore, that in evaluating future space systems, major emphasis should be given to basic design simplicity."²²

It should be noted that simplicity does not mean reliance on old technology. An integrated circuit chip replaces hundreds or thousands of earlier-generation electronic components, with a commensurate increase in reliability.

The spacecraft-level redundancy approach has one stumbling block when applied to space - the current high cost of launch. If even a small launcher costs well over \$10M, it doesn't matter if the payloads are cheap. Widespread adoption of the MAP requires that Microsat launch costs be lowered.

There are short- and long-term approaches to this problem being pursued. The short-term approach is cheaper expendable launch vehicles (ELVs). The Microcosm Sprite, a simplified liquid-fuel vehicle being designed with AFRL support will cost under \$2M to launch 200 kg into orbit. Another AFRL concept, a minimal launch vehicle launched from an F-15 aircraft, will cost as little as \$1M for each 40-kg payload orbited, if the number produced is high enough. Longer-term approaches under study include reusable launchers, such as the Space Maneuver Vehicle (SMV).

Acquisition

Finally, historical examples, as well as studies for AFSPC and AFRL, demonstrate that streamlined, cost-effective acquisition is a reality for Microsats, enabling savings in time and money compared to the acquisition system used for traditional space systems.

Integrating The MAP

If some space functions can be undertaken by low-cost Microsats or Microsat constellations, several advantages can be applied to space system acquisition. These include:

Mass production

Space systems are traditionally unique. Even the GPS satellites, built in "blocks," are all at least slightly different from one another. True mass production of spacecraft has only been applied in a few cases, such as Globalstar's 72 satellites or Orbcomm's 36.

Reduced oversight

A simpler system requires less oversight per unit produced. The reams of government and contractor experts (normally including contractors hired to check other contractors) who examine every MILSTAR satellite do not similarly scrutinize every cruise missile. That is not only because of the number produced, but because of the relative simplicity of the system. It's also because, thanks to the purchase of backup units, not every cruise missile needs to operate with 100 percent reliability.

Allowance for reasonable failures

Failure of a largesat such as MILSTAR represents a huge investment in the satellite, launch vehicle, launch campaign costs, etc. Such systems are inspected and tested exhaustively – and expensively – because they cannot be allowed to fail. When they do, significant portions of the military's satellite capability are lost. A related advantage is the opportunity to cancel unpromising programs. The Aerospace study of FBC cited earlier commented, "The flexibility provided by the ability to cancel programs in trouble...would have been very difficult to achieve with traditional programs due to the sheer magnitude of the sunk costs of these programs."²³

Reliance on larger numbers of small satellites spreads out the risk. It may take dozens of Microsats to equal, say, the capacity of a UFO. They may cost more, in total, than the largesat they replace. If the UFO fails,

however, 100 percent of the capability is lost. If three of the Microsats fail, a few percent of the capability has been lost. The ability to accept some risk allows us to further cut the overhead costs of test and inspection.

Increased contractor base

As mentioned earlier, the number of American companies serving as prime contractor for large satellites has been cut to four - Boeing (including Hughes), Lockheed-Martin, TRW, and Space Systems Loral. A reduction in the number of vendors most often means a reduction in competition, with a commensurate increase in price and decrease in innovation. If smaller satellites are considered as solutions, numerous additional vendors are available. These include established aerospace companies like Ball, relative newcomers such as Spectrum Astro, AeroAstro, and SpaceDev, and university-affiliated programs including the Space Dynamics Laboratory, One Stop Satellite Solutions, and others. Many of these organizations have gained reputations for innovative, low-cost designs with high success rates - Ball, for example, has built over thirty spacecraft with a zero failure rate. OSC's novel Orbcomm communications satellites have proven nearly as reliable.

Applying Microsat Lessons

An April 2000 workshop that brought together executives from some of the leading Microsat development organizations (commercial and university-based) produced consensus on some guidelines for successful low-cost spacecraft development programs. While these are derived from Microsat examples, they apply to most spacecraft programs.²⁴

- Focus on the mission. Avoid expanding the mission during development or adding secondary functions. Secondary missions, if truly important, can be addressed with their own dedicated Microsats.
- Small teams. Spacecraft should be built by integrated, cross-functional teams where each person has a good understanding of the entire spacecraft and its mission.
- Use commercial-off-the-shelf (COTS) parts with proper testing. Overreliance on milspec or space-qualified parts adds weight, prevents use of the most current technology, and adds to parts count, reducing reliability, all with no proven benefits.

- Accept risk. Attempts to avoid all risk by adding redundancy, sticking to space-qualified parts, etc. add high cost with little return.
- Stick to the schedule. Schedule and cost are closely related. It's cheaper to spend money to keep the program on schedule than it is to extend the schedule.
- Incentivize the contractor. Moving to less expensive Microsats creates room to fund contract incentives which reward innovative, low-cost, on-schedule designs with acceptable performance capabilities.

A second Aerospace Corporation study, an analysis of the failures in NASA's FBC programs completed in May 2000, reported that the failure was most likely when high complexity was combined with a short development timeline. There was no direct correlation between success and cost. Mismanagement and miscommunication were cited as major contributors to failure as well.²⁵ The Aerospace analysis indicates that, if the emphasis on schedule recommended by the workshop participants is to be followed, the emphasis on keeping the spacecraft simple needs to be given equal weight.

A final example to mention is the Amateur Radio Satellite Corporation (AMSAT) which makes full use of all the approaches just mentioned and uses not just COTS parts, but scrounged and donated parts. (One AMSAT spacecraft used a bus that was never intended to be flight hardware, but was built as a mock-up. It worked.²⁶) AMSAT spacecraft, ranging from a tiny 5-kg radio beacon to 140-kg, three-axis-stabilized communications satellites, to date include over 40 missions with only one on-orbit failure.²⁷

Recommendations

Resting on the three pillars described above, the MAP approach would recommend the following features in acquiring new space systems.

- Research the history. Space systems are often purchased with no knowledge of what historical examples may be relevant. For example, it is often assumed that the approach embodied by large satellites is the best way to perform a mission without knowing whether that mission has ever been done with small satellites. High-resolution imagery is the ONLY current mission for which small-satellite technology has never been developed.
- Use the smallest, simplest spacecraft that will perform the mission. In many cases, this means accepting an 80 percent solution – not because

100 percent isn't possible, but because pursuing the 100 percent goal would add years to the schedule and many millions to the cost.

- Do not automatically assume that contracting out the major part of development and even production is always the best way to go. In-house development has sometimes, as in the case of SolRad/GRAB, proved to be fast and efficient.

The Total Picture

The apparent cost of any system – even the LCC – does not give the entire picture of that system's ripple effects on military organizations, competing priorities, and other affected areas. For example, the increased interest in Microsats by non-DoD organizations, such as NASA, universities, and private industry, means a shift to the MAP would also facilitate industrial base maintenance and civil-military integration.

Conclusions

While not all DoD space missions can transition to Microsats, enough of them can to make the MAP the dominant model for future space acquisitions. Many lessons of the MAP can be applied to larger space systems as well.

Due to the volatile state of the DoD space budget, agencies guiding Microsat programs must do their jobs well. Any program which is controversial, as Microsats often are, must be solidly linked to requirements, satisfy a clear need, and contribute to the sponsoring command's vision for space capabilities. Because Microsats make easy targets when money is needed to fund cost overruns on larger, "more important" space systems, Microsat program managers must follow the MAP very carefully. The technology being pursued must be sound, the applicable requirements must be satisfied well, and a feasible, coherent, attainable acquisition plan must be in place.

The DoD approach to space is not merely inefficient. It is broken. A space system delivered on time and on budget is virtually unheard of. Needed capabilities slip for years because of the desire to maximize each spacecraft's functions, test it to (sometimes beyond) the point of damage, and ensure it has the latest technology.

The MAP offers a way out – not a cure-all, but certainly a major leap forward. Buying smaller, distributed systems and buying them efficiently means the military will have needed space systems as soon as possible for reasonable prices. Implementing the MAP requires the shattering of long-established paradigms

and, quite possibly, the restructuring or elimination of some elements of the military space acquisition system. It will require changes in the government-contractor relationship, with the government playing a greater role, in some cases, in R&D, while playing a smaller role in production of a system. Implementing the MAP will involve some difficulty, and possibly some risk. Not implementing keeps us on today's path – a totally unacceptable road to never-ending cost and schedule creep.

DISCLAIMER: Opinions in this paper are solely those of the authors. This paper does not represent any type of official position, plan, or policy of the U.S. Air Force, the Department of Defense, any agency of the U.S. government, Analytic Services Inc. (ANSER), SenCom, or any other corporation.

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¹ "Navy Scraps Polar Satellite Plan," *Space News*, 28 September - 4 October 1992, 2.

² An eight-Orbcomm constellation would provide continuous connectivity at low inclinations. Theaters at higher latitudes may require more satellites to avoid brief gaps in coverage. Whether there are gaps depends on the orbital altitude, transmitter and antenna design, and other factors.

³ This cost estimate adds Orbcomm's 1998 per-satellite cost estimate of \$2.5-3M to the \$15M cost of a Pegasus XL launch when the entire launch vehicle is purchased. The UFO cost is from "FY97 Annual Report," <http://www.dote.osd.mil/reports/FY97/navy/97ufo.html>, 12 August 1998.

⁴ Beneski, Barron, Orbital Sciences Corporation, personal communication, 12 August 1998; Slimmer, F., Hughes Space and Communications Media Relations, personal communication (12 August 1998).

⁵ Quoted in Fleeter, Rick, *The Logic of Microspace*. El Segundo, CA: Microcosm Press, 2000.

⁶ Wertz, J., "Lessons Learned from the Case Study Missions," in James Wertz and Wiley Larson, eds. *Reducing Space Mission Cost*. Torrance, CA: Microcosm Press, 1996, 13, 426, 486.

⁷ Larson, W., "Radical Cost Reduction Methods," in James Wertz and Wiley Larson, eds. *Reducing Space Mission Cost*, Microcosm Press, Torrance, CA, 1996, 37.

⁸ Air University, *Spacecast 2020*, 22 June 1994, J-18.

⁹ Cover, W., OSC, personal communication, 19 August 1998.

¹⁰ Air Force Scientific Advisory Board, *New World Vistas: Air and Space Power for the 21st Century*, 15 December 1995; *Air Force 2025*, 17 June 1996; Air University, *Spacecast 2020*, 22 June 1994.

¹¹ *New World Vistas*, Summary Volume, 43, Space Applications Volume, xxiii, and Space Technology Volume, 74.

¹² Bradley, B., et. al., Spacenet: On-Orbit Support in 2025," *Air Force 2025*, 17 June 1996, 26.

¹³ Martin, Donald H., *Communication Satellites 1958-1992*, Aerospace Corporation, El Segundo, CA, 31 December 1991, 95-7.

¹⁴ "Milstar Satellite Communications System," USAF fact sheet, November 1999: "Success Story - Milstar," http://www.safaq/hq.af.mil/acq_ref/stories/milstar.html, 26 November 1996.

¹⁵ "GRAB - World's First Reconnaissance Satellite," fact sheet, <http://ncst-www.nrl.navy.mil/HomePage/GRAB/GRAB.html>, no date, accessed 9 Jun 00.

¹⁶ Mosher, Todd, *et. al.* "Evaluating Small Satellites: Is the Risk Worth It?" Paper #SSC99-IIA-1, Proceedings of the 13th AIAA/USU Conference on Small Satellites, 23-36 August 1999.

¹⁷ Young, *et. al.* "Mars Program Independent Assessment Team Summary Report, " 14 March 2000.

¹⁸ AFSPC/DRCS, "Microsatellite Technology and Requirements Study," 31 December 1999.

¹⁹ "Microsatellite Technology and Requirements Study," *ibid.*

²⁰ The current version of the Tomahawk cruise missile costs \$600,000. Source: "Tomahawk Cruise Missile," U.S. Navy fact sheet, <http://www.chinfo.navy.mil/navpalib/factfile/missiles/wep-toma.html>, no date, accessed 28 January 1999.

²¹ Larson, W., "Radical Cost Reduction Methods," in James Wertz and Wiley Larson, eds. *Reducing Space Mission Cost*. Microcosm Press, Torrance, CA, 1996, 51.

²² Report of the Committee on Science and Astronautics, U.S. House of Representatives, "Ways and Means of Effecting Economies in the National Space Program," Government Printing Office, Washington, D.C.: 21 December 1962, 3.

²³ Mosher, *ibid.*

²⁴ This is a synthesis of the points presented by attendees at the AIAA Space Operations and Support Technical Committee (SOSTC) 6th Annual Workshop on Lowering the Cost of Space Operations, 11-12 April 2000. Contributors included Dr. James Wertz, CEO of Microcosm; Dr. Jay Smith of One Stop Satellite Solutions; David Goldstein, vice president, AeroAstro, and Matt Bille of ANSER. This list also incorporates separate comments by Dr. Jan King of SpaceDev in an April 1998 interview with Matt Bille.

²⁵ Dornheim, M., "Aerospace Corp. Study Shows Limits of Faster-Better-Cheaper," *Aviation Week*, 12 June 2000, 47.

²⁶ King, J., interview with Matt Bille (April 1998).

²⁷ Wertz, J., "Lessons Learned from the Case Study Missions," in James Wertz and Wiley Larson, eds. *Reducing Space Mission Cost*. Microcosm Press, Torrance, CA, 1996, 12.